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MHD Modeling of Differential Rotation in Coronal Holes

Roberto Lionello

Jon A. Linker

Zoran Mikić

Pete Riley

Roberto.Lionello@saic.com, Jon.A.Linker@saic.com, Zoran.Mikic@saic.com, Peter.Riley@saic.com

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Summary

- The photosphere and the magnetic flux therein undergo differential rotation.
- Coronal holes appear to rotate almost rigidly.
- Magnetic reconnection has been invoked to reconcile these phenomena.
- Mechanism relevant to the formation of the slow solar wind.
- We have used our MHD model in spherical coordinates to study the effect of differential rotation on coronal holes.
- We have imposed a magnetic flux distribution similar to Wang et al. (1996), and applied differential rotation for the equivalent of 5 solar rotations.

Boundary Conditions

- We assume uniform density and temperature at the base of the corona.
- We model differential rotation using the following formula as a function of latitude.

$$\omega(L) = -27.7 \sin^2 L \text{ degrees day}^{-1}.$$

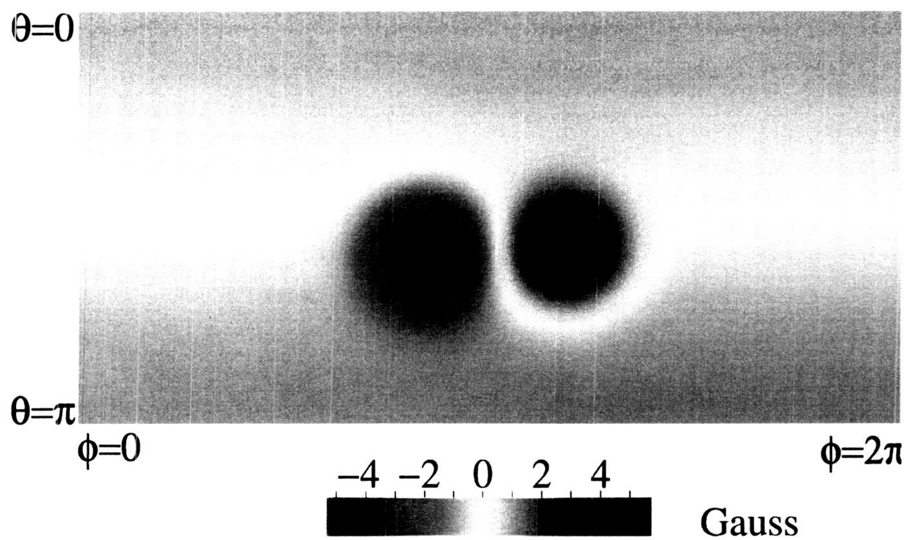
  The amount of differential rotation is ten times the solar value.
- Radial velocity on the solar surface is calculated solving the characteristics equation.
- The flow at the outer boundary is super-sonic and super-Alfvénic.

The Polytropic MHD Model

$$\begin{aligned}
\nabla \times \mathbf{A} &= \mathbf{B}, \\
\frac{\partial \mathbf{A}}{\partial t} &= \mathbf{v} \times \mathbf{B} - \frac{c^2\eta}{4\pi}\nabla \times \mathbf{B}, \\
\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\mathbf{v}) &= 0, \\
\frac{1}{\gamma - 1}\left(\frac{\partial T}{\partial t} + \mathbf{v}\cdot\nabla T\right) &= -T\nabla\cdot\mathbf{v}, \\
\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) &= \frac{\nabla \times \mathbf{B} \times \mathbf{B}}{4\pi} - \nabla p + \rho\mathbf{g} + \nabla\cdot(\nu\rho\nabla\mathbf{v}), \\
\gamma &= 1.05.
\end{aligned}$$

Initial Conditions

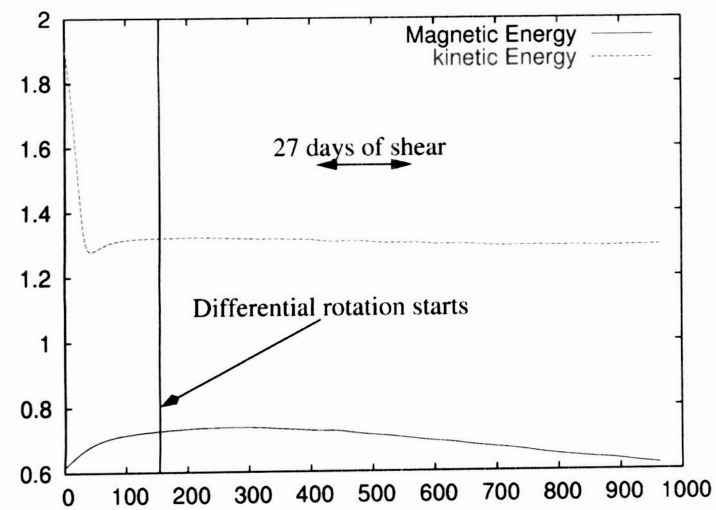
- We start from a magnetic flux distribution on the solar surface consisting of a dipole field with 1G intensity at the poles plus a bipolar "active region". This flux distribution is similar to that of Wang, Y.-M., Hawley, S. H., and Sheeley Jr., N. R., *Science*, **271**, 464, 1996.



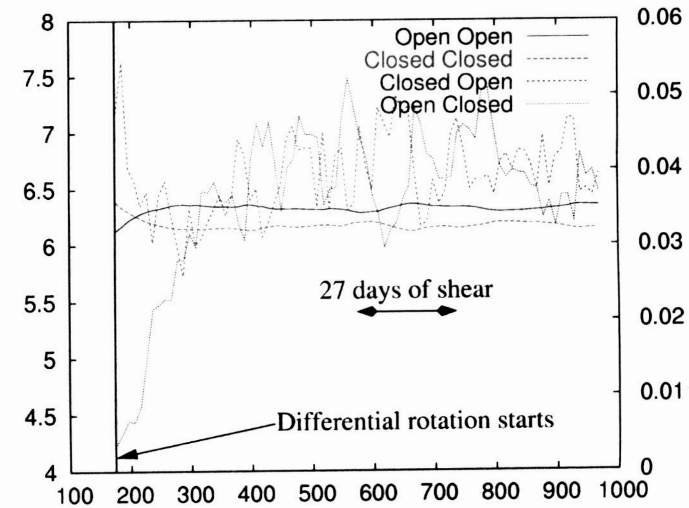
- A Parker's solar wind solution is used to determine the initial velocity, density, and temperature in the corona.

The Simulation

- After an initial period of relaxation towards an MHD steady state with solar wind, differential rotation is applied to the system. The total shear applied amounts to that of 5 rotations on the Sun.

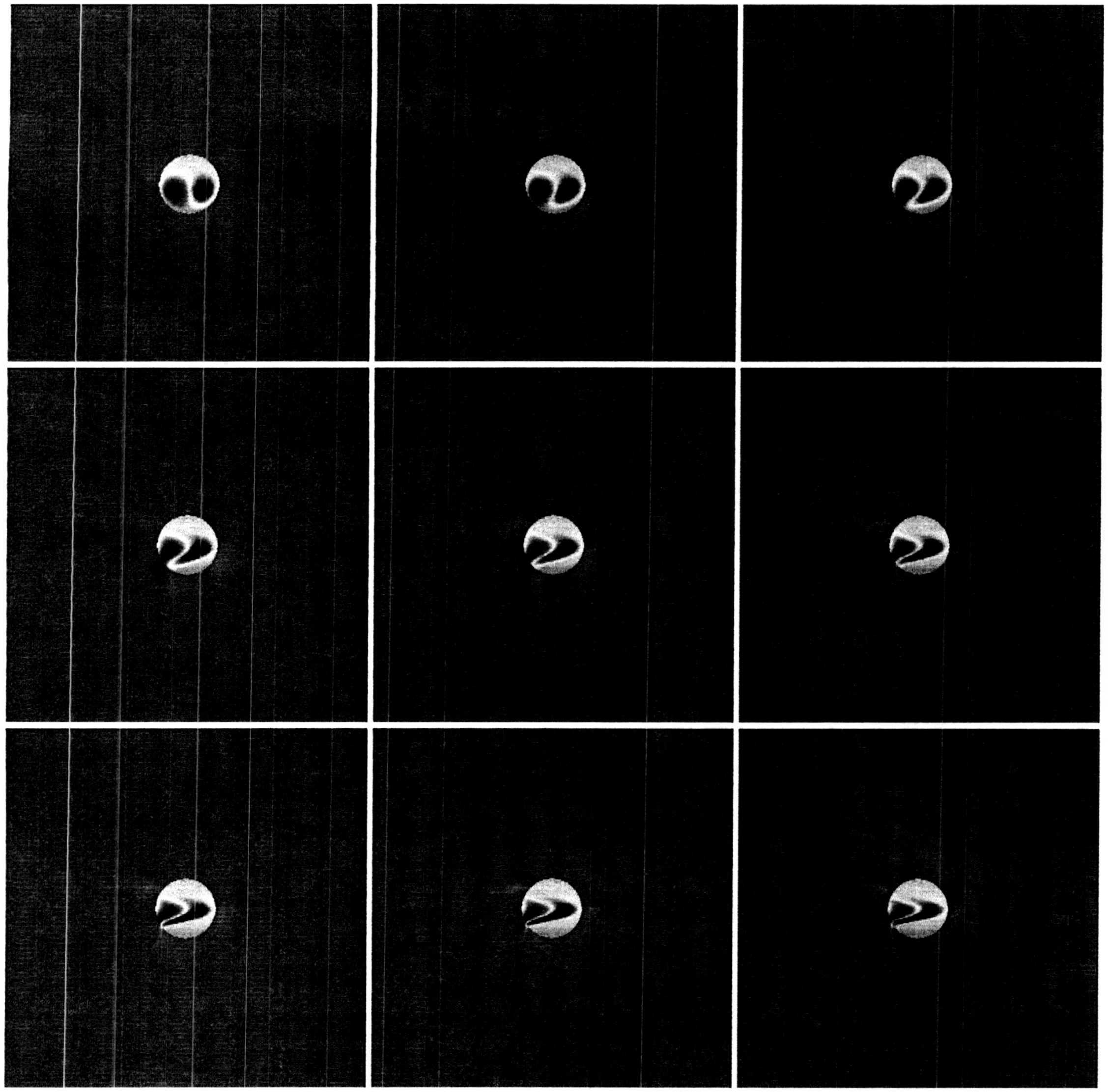


Magnetic and kinetic energy during the simulation.



Sun's areas where the magnetic flux remains open or closed, and areas where it opens up or closes down.

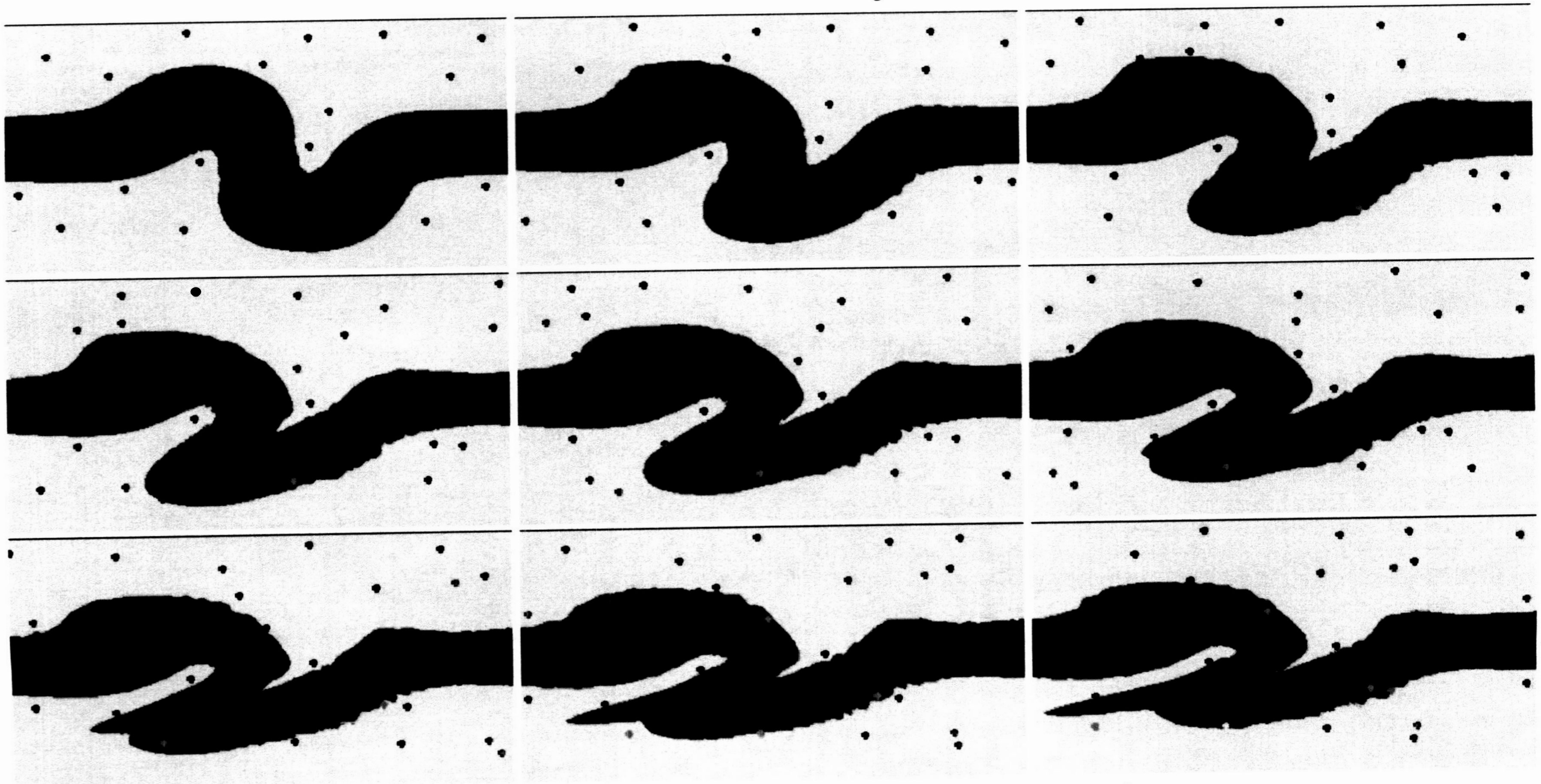
Pb and B_r Evolution



$\Delta t = 16.8$ Days

Coronal Holes Maps

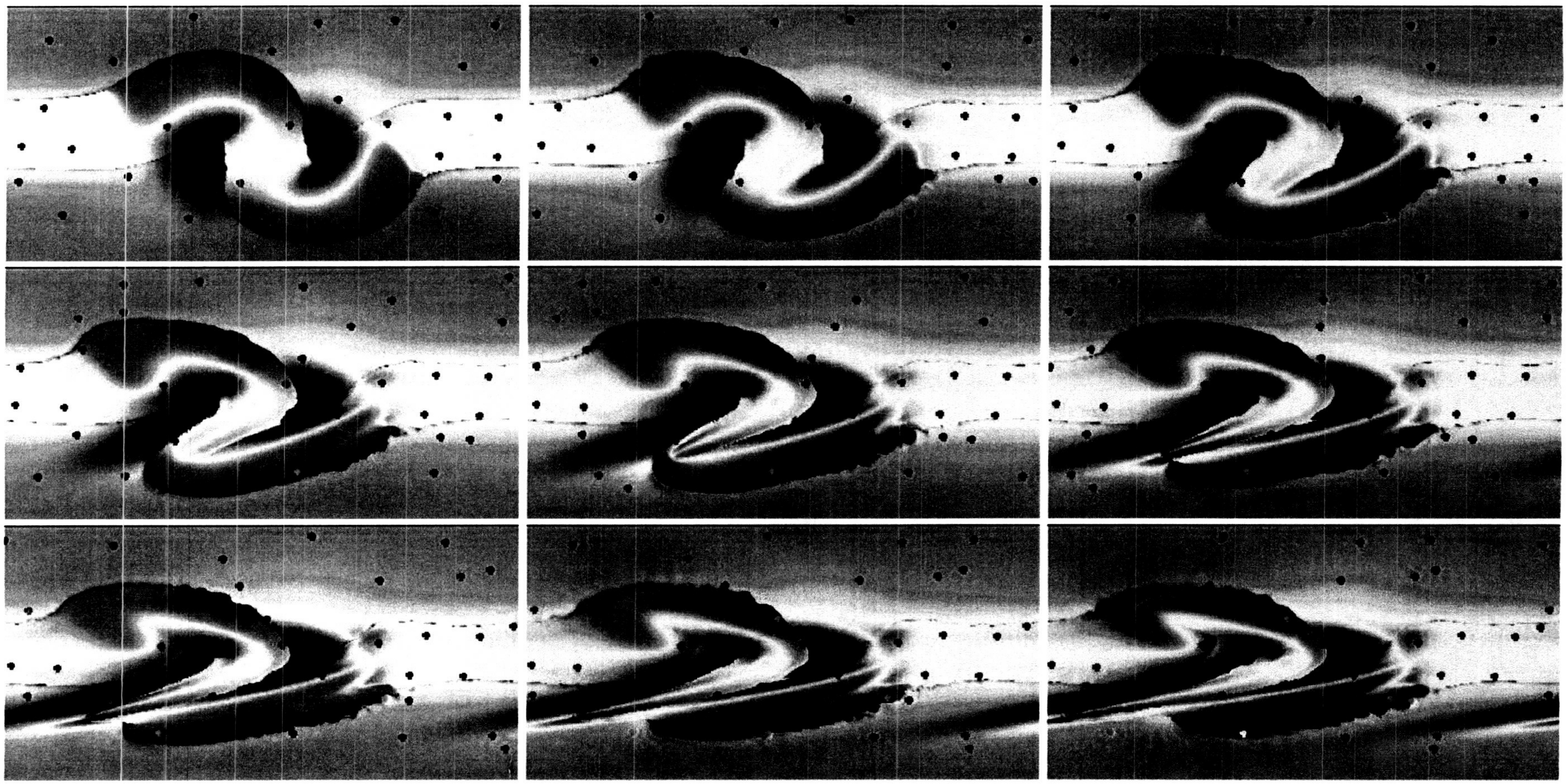
$\Delta t = 16.8$ Days



Black: launch points of open field lines; green: line closed down; cyan: line reopened;
Red: launch points of closed field lines; blue: line opened up.

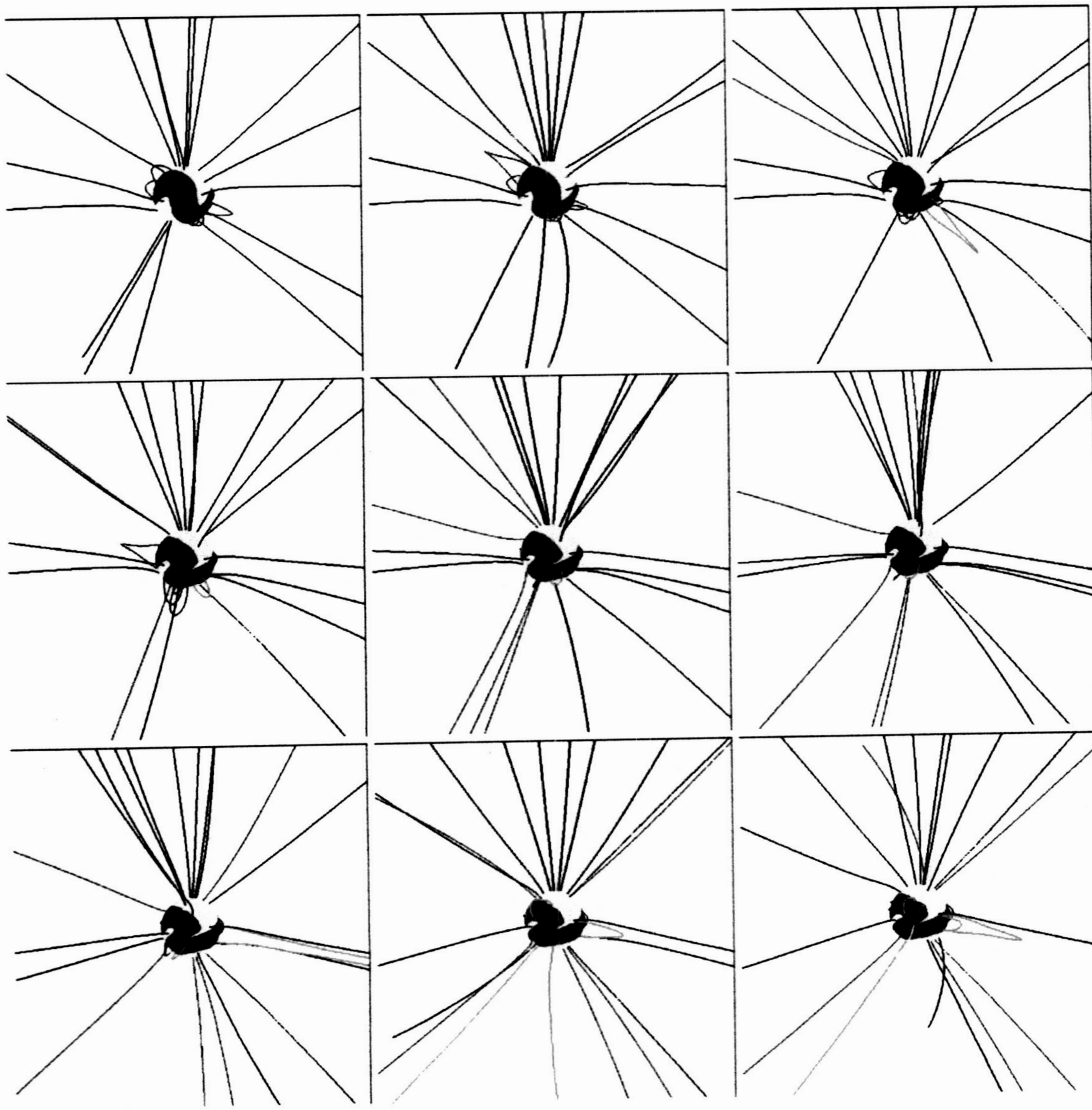
K Maps

$\Delta t = 16.8$ Days, $K = \log(r_1^2 B_1) - \log(r_2^2 B_2)$



Black: launch points of open field lines; green: line closed down; cyan: line reopened;
Red: launch points of closed field lines; blue: line opened up.

Magnetic Field Lines and CH Maps

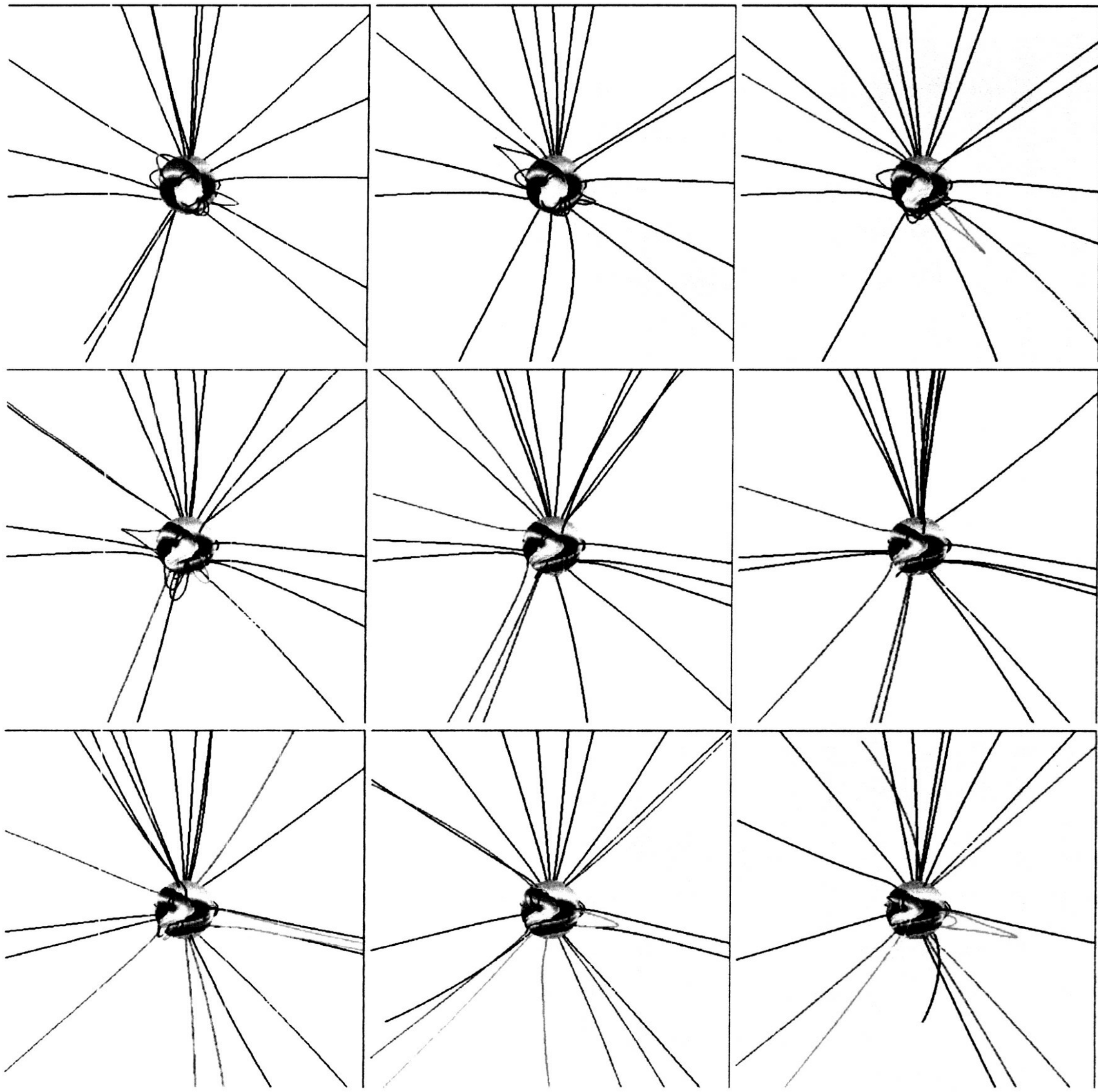


$\Delta t = 16.8$ Days

Black: initially open field lines;
green: line closed down;
cyan: line reopened;

Red: initially closed field lines;
blue: line opened up.

Magnetic Field Lines and K Maps



$\Delta t = 16.8$ Days

Black: initially open field lines;
green: line closed down;
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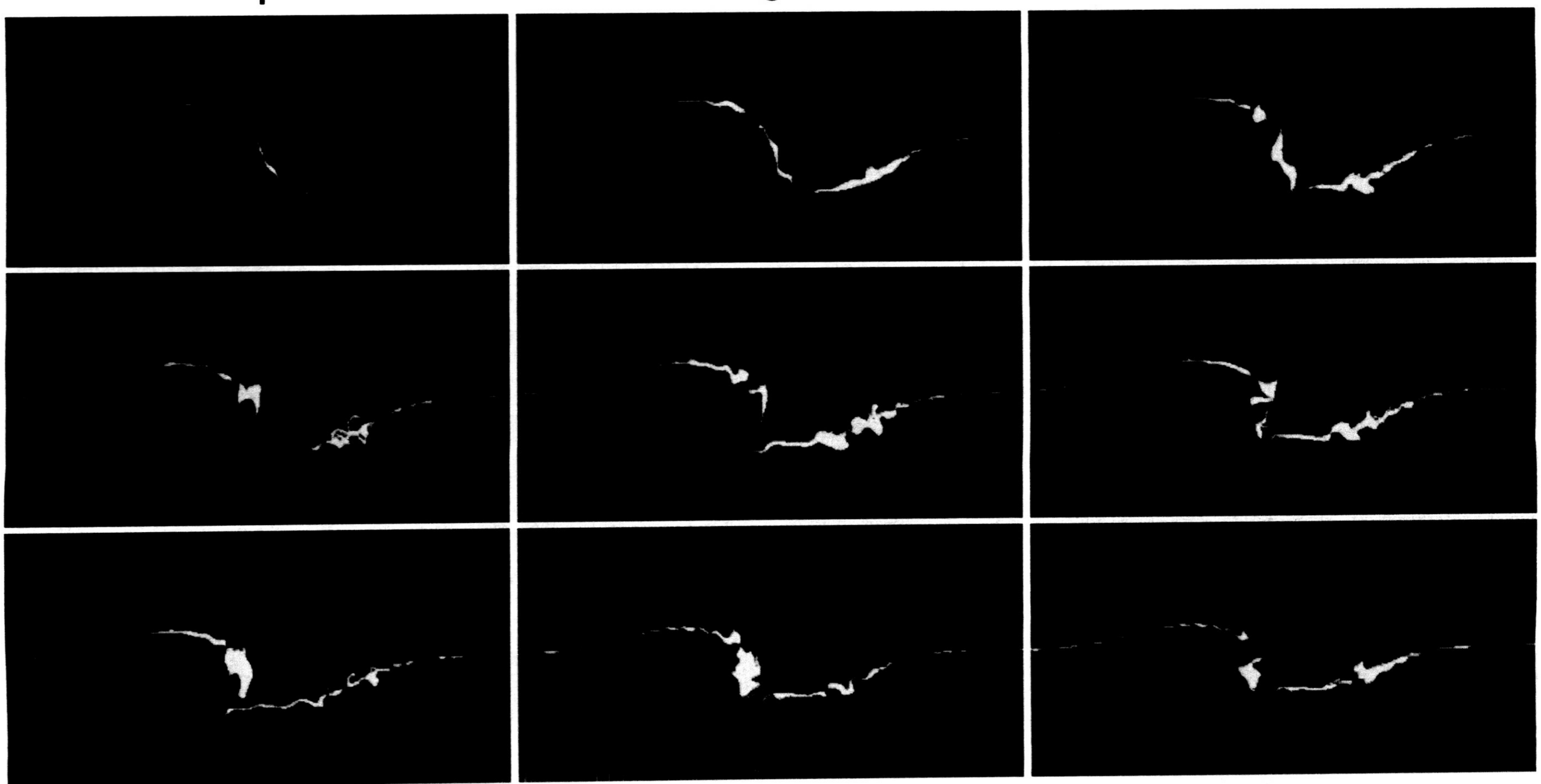
Connectivity at 30 $R_\odot$

Maps are taken at 30 $R_\odot$ with $\Delta t = 16.8$ days



Green: regions connected from 30 $R_\odot$ to the solar surface. Yellow: regions disconnected from the solar surface.

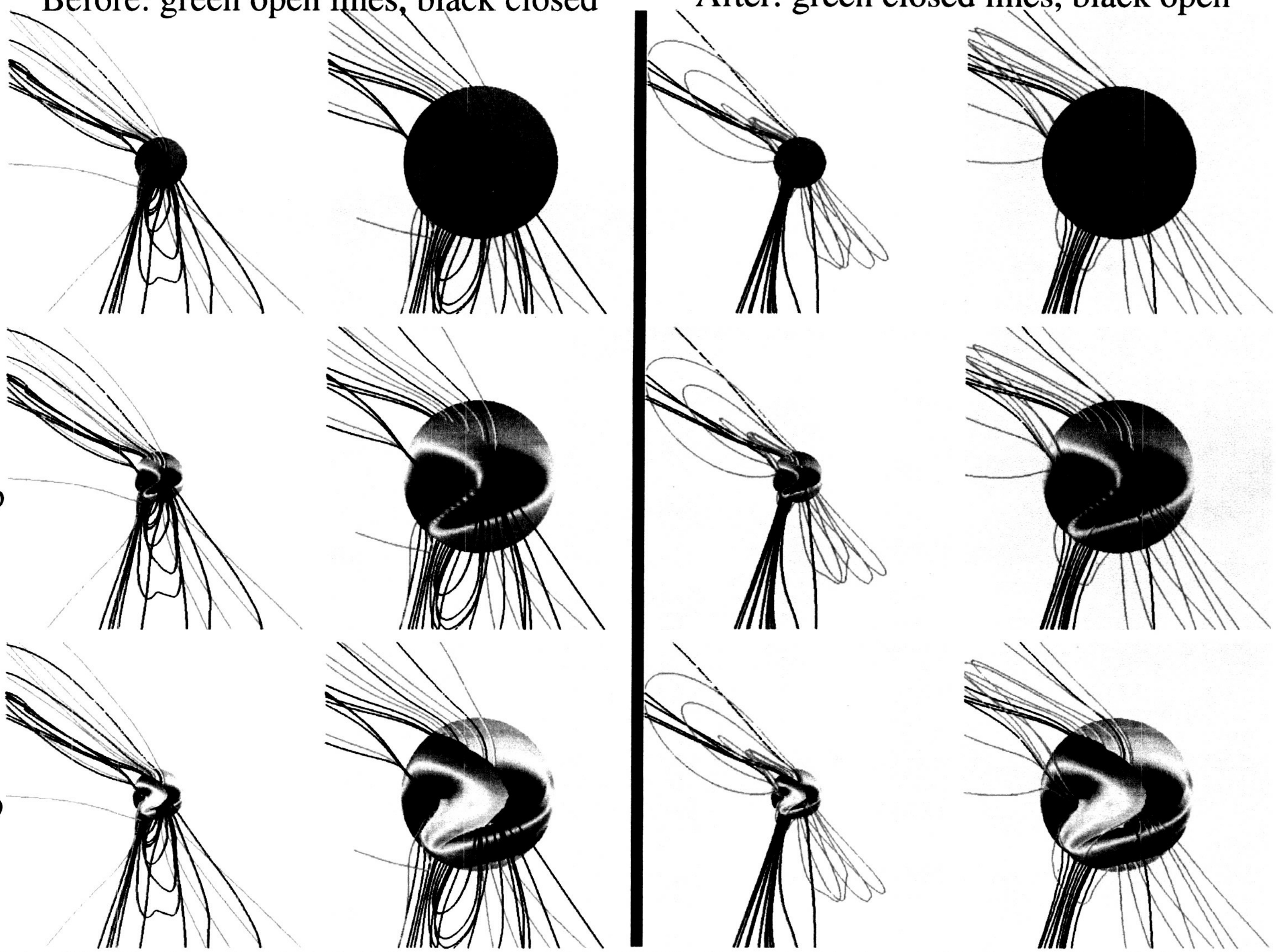
Some Reconnection Events

Before: green open lines, black closed | After: green closed lines, black open

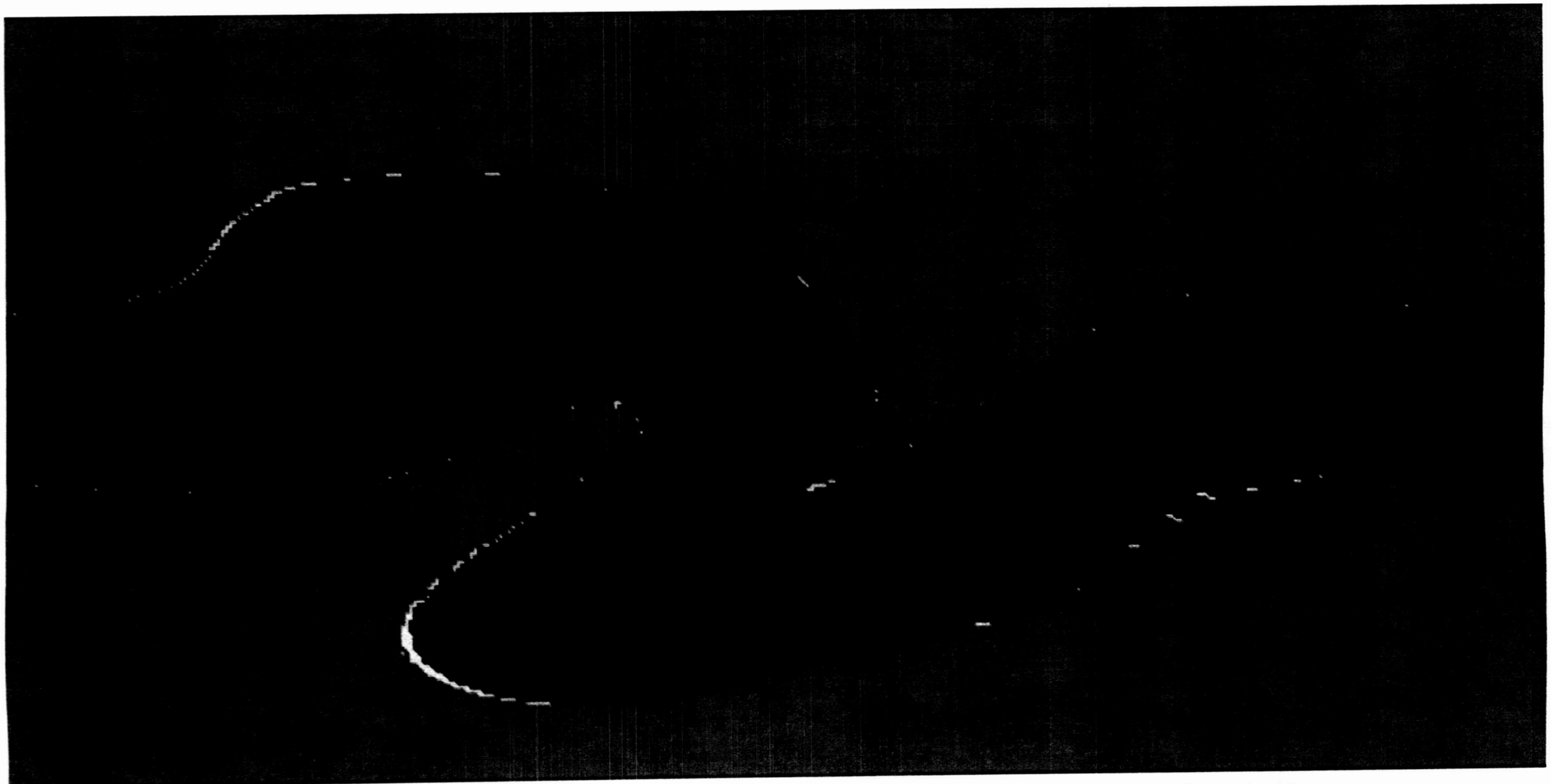
CH Map

B_r Map

K Map



Slow Wind Sources



Each field launch point is subject to differential rotatation. $x(\theta, \phi(t_2))$ is compared with $x(\theta, \phi(t_1))$, with $t_2 > t_1$. Regions that remain open are blue, regions that remain closed are dark red, regions that open up are white (slow wind sources), regions that closed down are red.

Conclusions

- The north pole hole extension remains substantially unchanged through differential rotation.
- The south pole hole extension is sheared considerably.
- A fluctuating fraction of the solar surface is occupied by magnetic flux that is opening up.
- Magnetic flux elements (i.e. field line launch points) enter and exit regions of open or closed flux.
- At 30 $R_{\odot}$, magnetic field lines unconnected with the surface or simply dipped are confined to the current sheet.
- This and the K factor plots argue in favor of magnetic reconnection at the current sheet.

Conclusions (cont.)

- Reconnection events are complicated. We have found some indication of reconnection of open field lines with loops with foot points lying close to the separatrix (surface of discontinuity in K).
- By comparing coronal hole maps it is possible to indicate the probable regions of origin of the slow solar wind at the boundary of coronal holes.
- There is good correspondence with what we have found and the scenario presented by Wang et al. (1996).